

## Light-collimating system

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The invention relates to a light-collimating system for collimating light.

Such light-collimating systems are known per se. They are used inter alia as backlight-collimating systems in (picture) display devices, for example for TV sets and monitors. Such light-collimating systems are particularly suitable for use as backlights for 5 non-emissive displays such as liquid crystal display devices, also denoted LCD panels, which are used in (portable) computers, TV sets or (portable) telephones.

Said display devices usually comprise a substrate provided with a regular pattern of pixels which are each controlled by at least one electrode. The display device utilizes a control circuit for achieving a picture or a data graphical display in a relevant field 10 of a (picture) screen of the (picture) display device. The light originating from the backlight in an LCD device is modulated by means of a switch or modulator, various types of liquid crystal effects being used. In addition, the display may be based on electrophoretic or electromechanical effects.

Such light-collimating systems are also used as luminaires for general lighting 15 purposes or for shop lighting, for example shop window lighting or the lighting of (transparent or semi-transparent) plates of glass or of synthetic resin on which items, for example jewelry, are displayed. Such light-collimating systems are further used as window panes, for example for causing a glass wall to radiate light under certain conditions, or to reduce or block out the view through the window by means of light. Further alternative 20 applications are the use of such light-collimating systems for illuminating advertising boards, drawing tables and X-Ray photographs.

In the light-collimating systems mentioned in the opening paragraph, the light source used is usually a tubular low-pressure mercury vapor discharge lamp, for example one or a plurality of cold-cathode fluorescent lamps (CCFL), wherein the light emitted by the 25 light source during operation is coupled into the light-emitting panel, which acts as an optical waveguide. This waveguide usually constitutes a comparatively thin and planar panel which is manufactured, for example, from synthetic resin or glass, and in which light is transported through the optical waveguide under the influence of (total) internal reflection.

As an alternative light source, such a light-collimating system may also be provided with a plurality of optoelectronic elements, also referred to as electro-optical elements, for example electroluminescent elements, for example light-emitting diodes (LEDs). These light sources are usually provided in the vicinity of or tangent to a light-transmitting edge surface of the light-emitting panel, in which case light originating from the light source is incident on the light-transmitting edge surface during operation and distributes itself in the panel.

10 Light-collimating systems are preferably embodied as direct-lit backlight-collimating systems when high emitted light intensities are desired and/or when large-area light-emitting surfaces have to be provided. Such a direct-lit backlight-collimating system is known from WO-A 97/36 131. The known backlight-collimating system comprises at least one light source, and a light-directing assembly in close proximity to the light source, the  
15 light-directing assembly comprising so-called micro prisms and blocking means between the micro prisms, the blocking means locally blocking the passage of light. In the known light-collimating system the light-blocking means are reflective elements while a reflector is positioned behind and/or around the light source, that is, in the direction away from the light-directing assembly, to redirect light rays propagating away from the light-directing assembly  
20 back towards the micro prisms. Employing specular and diffusely reflecting materials, this preferred embodiment increases the total available light output and efficiency of the backlight-collimation system. A drawback of the known light-collimating system is that the light-collimating system has a fixed collimation angle.

25 It is an object of the invention to eliminate the above disadvantage wholly or partly. To meet the object of the invention, the light-collimating system includes:

a plurality of elements, each element including at least a first wall and at least a second wall,

30 the first wall of an element and the second wall of an adjacent element being spaced with respect to each other at a side of the light-collimating system facing the light source, said spacing between said first wall and said second wall defining an aperture window for admitting light from the light source into the light-collimating system,

the first wall of said element and the second wall of said adjacent element forming a wedge-shaped structure widening in a direction facing away from the light source, the first wall and the second wall at a side facing the wedge-shaped structure being provided with a specular reflecting surface,

5 the wedge angle  $\theta_w$  of the first wall and the second wall with respect to the normal on the aperture window being adjustable for enabling adjustable collimation.

In the light-collimating system according to the invention, light collimation results from specular reflections from the walls of the wedge-shaped structures. In the known light-collimating system collimation of light is brought about by the total internal reflection 10 (TIR) of incident light from the optically smooth walls of the micro prisms.

In the light-collimating system according to the invention, the wedge-shaped structures are open, hollow structures (filled with air, refractive index  $n=1$ ). Depending on the design of the wedge-shaped structures, successive reflections may occur in the wedge-shaped structure, which is advantageous for obtaining a large aperture of the light-collimating 15 system. Preferably, the first and second walls are made from a sheet material. Such sheets can easily be drawn into the desired shape, for instance, by a thermal deep-drawing process. In the known light-collimating systems, the wedge-shaped micro prism structures are made from a solid transparent material. The micro prisms in the known light-collimating system have a refractive index which corresponds to the refractive index of the material from which 20 the prisms have been made (generally the refractive index is  $n \approx 1.5$ ).

According to the invention the wedge angle  $\theta_w$  of the first wall and the second wall is adjustable. The shape of the wedge-shaped structures is changed when the wedge angle is changed. By adapting the shape of the wedge-shaped structures, the propagation direction of reflected light from the first and/or the second wall changes thereby influencing 25 the way in which light is collimated by the wedge-shaped structures. The light issuing from the light-collimating system according to the invention accordingly has an adjustable degree of collimation.

In the description of this invention, the hollow wedge-shaped structure is also addressed as a (hollow) wedge collimator.

30 A preferred embodiment of the light-collimating system according to the invention is characterized in that an adjustable positioning plate supports the first wall and the second wall at a side facing away from the wedge-shaped structure, by moving the positioning plate in a direction away from the aperture window the wedge angle  $\theta_w$  becoming smaller, and vice versa. By moving the adjustable positioning plate "up" and "down" with

respect to the aperture window the wedge angle  $\theta_w$  of the first wall and the second wall with respect to the normal on the aperture window becomes smaller and larger, respectively. In this manner adjustable collimation of the light-collimating system according to the invention is realized. The movement of the adjustable positioning plate can for instance be done by the 5 user of the light-collimating system either by mechanical means or by remotely-controlled electro-mechanical means.

Preferably, the wedge angle  $\theta_w$  ranges between approximately 0° and approximately 25°. When the wedge angle  $\theta_w \approx 0^\circ$  the adjustable positioning plate is in the highest position (remote from the aperture window), whereas when the wedge angle  $\theta_w \approx 25^\circ$  10 the adjustable positioning plate is in the lowest position (close to the aperture window). When the wedge angle is large, the collimation angle  $\theta_c$  is small, i.e. a relatively narrow beam of light is issued by the light-collimating system. Preferably, the wedge angle  $\theta_w$  ranges between approximately 0° and approximately 15°.

A preferred embodiment of the light-collimating system according to the 15 invention is characterized in that the wedge-shaped structure is configured from a plurality of walls forming a diaphragm-like wedge-shaped structure. The plurality of walls, comprising at least one first wall and at least one second wall, function as (reflective) side flaps of the diaphragm-like wedge-shaped structure. The plurality of first and second walls slide past each other when the wedge angle  $\theta_w$  of the walls is changed.

20 A preferred embodiment of the light-collimating system according to the invention is characterized in that the first wall and the second wall are straight walls. The resulting so-called cone-shaped open wedge-shaped structure is relatively easy to manufacture.

An alternatively preferred embodiment of the light-collimating system 25 according to the invention is characterized in that the first wall and the second wall are curved, preferably, parabolically-shaped walls. A curved or parabolically-shaped wedge is more difficult to manufacture, but is optically more efficient since it allows a certain degree of light collimation to be attained at a larger aperture at no more than only a single specular reflection from the parabolically-shaped walls.

30 A preferred embodiment of the light-collimating system according to the invention is characterized in that the first wall and the second wall of each element are provided on a supporting member at a side facing away from the light source, and that the supporting member between the first wall and the second wall of each element is provided

- with a light-reflecting element comprising a specular and/or diffuse reflecting material. Light produced inside the backlight-collimating system is allowed to escape from the light-collimating system only through the aperture-window between the first wall of an element and a second wall of an adjacent element, i.e. at the location of the wedge-shaped structures.
- 5 Light is not allowed to be transmitted into the cavity between the first and second wall of an element. By providing a reflective element between the first and second wall of an element, light is effectively and efficiently back-reflected and subsequently recycled in the backlight-collimating system.

Reflective layers and/or coatings are usually present in any application involving efficient light recycling, light (re)distribution, light transport, and light collimation. Imposed demands on the reflective materials comprise the absence of light absorption within the visible wavelength region, the absence of absorption-induced colour shifts, a high resistance to chemical degradation under the (combined) influence of heat, light, humidity, and an availability at low cost while being easy to process/manufacture. Suitably performing reflective layers are layers of dry binder-free inorganic powder particles. Preferably, the specular reflecting material is selected from the group formed by aluminum and silver and the diffuse reflecting material is selected from the group formed by aluminum oxide, barium sulfate, calcium-pyrophosphate, titanium oxide and yttrium borate. Preferably, the first and second wall of the elements are specularly reflecting, for instance by making the wall of a specularly reflecting material, e.g. aluminum or silver, or by coating the wall with an aluminum or silver layer. The other materials very efficiently contribute to light recycling in (back) light-collimating systems. Preferably, the diffuse reflecting powder material is mixed with particles of Alon-C powder (a gamma-structure aluminium oxide powder (Degussa) possessing an average primary particle size of approximately 20 nm). When calcium-pyrophosphate powder, possessing an average particle diameter of at least 5  $\mu\text{m}$ , is mixed with 1% w/w Alon-C powder, the resulting powder mixture behaves like a so-called free-flowing powder.

A preferred embodiment of the light-collimating system according to the invention is characterized in that the first wall and the second wall are made from glass, metal or plastic. Preferably, the open wedge structure can be created by e.g. a thermal deep-drawing process of an optically smooth aluminum sheet or a plastic PET sheet that is coated with an aluminum or silver layer. The aluminum sheet or layer functions as the specular reflecting surface. The aperture windows, i.e. the space, at the location of the supporting member, between the first wall of an element and a second wall of an adjacent element

remain transparent for light. The aperture windows are preferably embodied as windows consisting of a transparent plastic or glass layer that is attached to the supporting member and that connects to the said first wall and second wall at the location of the supporting member thereby maintaining a fixed width of the aperture window.

5 A preferred embodiment of the light-collimating system according to the invention is characterized in that, at the location of the first and second wall facing the light source, e.g. at the location of the supporting member, the distance  $d_{sp}$  between the first wall and the second wall of each element is larger than the wavelength of visible light. By selecting the distance  $d_{sp}$  substantially larger than approximately 500 nm, preferably  
10 <characterizing portion of claim 12>  $d_{sp} \geq 10 \mu\text{m}$ , light diffraction phenomena in and around the wedge structures are avoided, thereby enabling that a diffraction-induced disturbance of the collimation performance of the wedge collimator structure does not occur.

15 A preferred embodiment of the light-collimating system according to the invention is characterized in that <characterizing portion of claim 13> the height  $h_w$  of the wedge-shaped structures is in the range  $0.5 \times d_{aw} \leq h_w \leq 50 \times d_{aw}$ , where  $d_{aw}$  is the distance between the first wall of an element and the second wall of an adjacent element at the location of the first and second wall facing the light source. If a supporting member is provided in the light-collimating system,  $d_{aw}$  is the distance between the first wall and the second wall at the location of the supporting member. With a height  $h_w$  in the given range  
20 isotropic light emitted by the light source inside the light-collimating system can be collimated to a collimation angle  $\theta_c$  within the range  $10^\circ \leq \theta_c \leq 90^\circ$ .

25 A preferred embodiment of the light-collimating system according to the invention is characterized in that the light-collimating system further comprises a lens assembly, comprising a plurality of lenses, each lens cooperating with one of the wedge-shaped structures. The obtained degree of collimation is further enhanced through the presence of an optional lens assembly on the light-emitting side of the wedge collimator.

A particularly simple light-collimating system is obtained through the measures according to the invention. The light issuing from the light-collimating system according to the invention has an adjustable degree of collimation.

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The invention will now be explained in more detail with reference to a number of embodiments and a drawing, in which:

Figure 1 is a cross-sectional view of an embodiment of the adjustable wedge collimator according to the invention for two different positions of the adjustable positioning plate;

Figure 2A is a cross-sectional view of an alternative embodiment of the 5 adjustable wedge collimator according to the invention;

Figure 2B is a cross-sectional view of a further alternative embodiment of the adjustable wedge collimator according to the invention;

Figure 3 is a top view of a diaphragm-like adjustable wedge-shaped structure;

Figure 4 shows a path of a light ray through a detail of the adjustable wedge 10 collimator, and

Figure 5 shows the collimation angle  $\theta_c$  as a function of the wedge angle  $\theta_w$  for the adjustable wedge collimator

The Figures are purely diagrammatic and not drawn true to scale. Some 15 dimensions are particularly strongly exaggerated for reasons of clarity. Equivalent components have been given the same reference numerals as much as possible in the Figures.

Figure 1 schematically shows a cross-sectional view of an embodiment of the adjustable wedge collimator according to the invention for two different positions of the 20 adjustable positioning plate 8. The light-collimating system of Figure 1 comprises a supporting member 1 for admitting light from a light source (not shown in Figure 1A and 1B; the direction of the incident light is indicated by the arrow  $L_{in}$ ) into the light-collimating system. The supporting member 1 is provided at a side facing away from the light source with a plurality of elements 2, 2', .... Each element 2, 2', ... includes at least a first wall 3, 25 3', ... and at least a second wall 4, 4', .... Preferably, the first wall 3, 3', ... and the second wall 4, 4', ... are made from glass, metal or plastic. The first wall 3 of an element 2 and the second wall 4' of an adjacent element 2' is spaced with respect to each other at a side of the light-collimating system facing the light source (in the example of Figure 1 at the location of the supporting member 1). The spacing between the first wall 3 and said second wall 4' 30 defines an aperture window 5, 5', ... for admitting light from the light source into the light-collimating system. The distance between the first wall 3 and the second wall 4' at the location of the aperture window is also referred to as the aperture width  $d_{aw}$ . The first wall 3 of the element with reference numeral 2 and the second wall 4' of the adjacent element 2' form a wedge-shaped structure widening in a direction facing away from the light source. In

addition, both the first wall 3, 3', ... and the second wall 4, 4', ... at a side facing the wedge-shaped structure are provided with a specular reflecting surface (see Figure 4), preferably made from silver or aluminum. An adjustable positioning plate 8 supports the first wall 3, 3', ... and the second wall 4, 4', ... at a side facing away from the wedge-shaped structure.

- 5 According to the invention, this positioning plate 8 can be moved up and down in a direction away from and towards the aperture window 5, 5', .... Depending on the position of the positioning plate 8 with respect to the aperture window 5, 5', ..., the wedge angle  $\theta_w$  becomes smaller or larger. In this manner the collimation provided by the light-collimating system becomes adjustable. In an alternative embodiment a lens assembly comprising a
- 10 plurality of lenses is provided on top of the first wall 3, 3', ... and the second wall 4, 4', ... (not shown in Figure 1). In the example of Figure 1, the first wall 3, 3', ... and the second wall 4, 4', ... are straight walls. In an alternative embodiment, the first wall and the second wall are curved walls, preferably, parabolically-shaped walls (not shown).

In the upper part of Figure 1 the adjustable positioning plate 8 is in its lowest position. The first wall 3, 3', ... and the second wall 4, 4', ... touch each other at the side facing away from the aperture window 5, 5', .... In this position, the wedge angle  $\theta_{w1}$  reaches its largest value. A very suitable value for wedge angle  $\theta_{w1} \approx 25^\circ$ . Particularly preferred is wedge angle  $\theta_{w1} \approx 15^\circ$ . In the lower part of Figure 1 the adjustable positioning plate 8 is shifted away from the aperture window 5, 5', ..., reaching a higher position. The first wall 3, 3', ... and the second wall 4, 4', ... no longer touch each other at the side facing away from the aperture window 5, 5', ... and the wedge angle  $\theta_{w2}$  diminishes. The minimum value for the wedge angle  $\theta_{w2} \approx 0^\circ$ . When the wedge angle  $\theta_w$  is large, the collimation angle  $\theta_c$  is small, i.e. a relatively narrow beam of light is issued by the light-collimating system. The broad arrows at the side of the two different positions of the adjustable positioning plate 8 in Figure 1 indicate that the variability of the light-collimating system enables an adjustable collimation angle. Preferably, the light-reflecting element 6, 6', ... of the adjustable positioning plate 8 facing the aperture window 5, 5', ... is provided with a light-reflecting element. This light-reflecting element 6, 6', ... reflects the light efficiently back and this back-reflected light is subsequently recycled in the backlight-collimating system.

30 Figure 2A shows a cross-sectional view of an alternative embodiment of the adjustable wedge collimator. In this embodiment the supporting member 1 between the first wall 3, 3', ... and the second wall 4, 4', ... of each element 2, 2', ... is provided with a light-reflecting element 16; 16', ... comprising a specular and/or diffuse reflecting material. In the

example of Figure 2A the light-reflecting element 16; 16', ... is embedded in the supporting member 1, e.g. in tunnels. The Figure 2B shows a cross-sectional view of a further alternative embodiment of the adjustable wedge collimator. In this embodiment the supporting member 1 between the first wall 3, 3', ... and the second wall 4, 4', ... of each element 2, 2', ... is 5 provided with a light-reflecting element 26; 26', ... in the form of a coating comprising a specular and/or diffuse reflecting material.

The specular or diffuse reflecting material of the light-reflecting element 6; 6', ...; 16; 16', ...; 26, 26', ... preferably comprises a powder material, the material selected from the group formed by aluminum oxide, barium sulfate, calcium-pyrophosphate, titanium 10 oxide and yttrium borate. Use of Ca-pyrophosphate with an average particle diameter between 8 and 10  $\mu\text{m}$  is particularly recommended because of its ready availability, cheapness, chemical purity, resistance to high temperatures ( $>1000^\circ\text{C}$ ), and its proven non-absorbing characteristics towards visible light within the  $\lambda = 400 - 800 \text{ nm}$  range after annealing at  $900^\circ\text{C}$  in air. When Ca-pyrophosphate is mixed with 1% w/w Alon-C nanoparticles, the resulting powder mixture behaves like a so-called free-flowing powder with 15 which the said tunnels in Figure 2A can be readily filled to form the reflective elements 16, 16', ....

At the location of the aperture window 5, 5', ..., the distance  $d_{sp}$  between the first wall 3, 3', ... and the second wall 4, 4', ... of each element 2, 2', ... is preferably larger 20 than the wavelength of visible light. Preferably, both the distances  $d_{sp}$  and  $d_{aw}$  are larger than 10  $\mu\text{m}$ . Preferably, the distance  $d_{sp}$  is larger than 1 mm. The latter makes the filling of the spaces between the first wall 3, 3', ... and the second wall 4, 4', ... with the particles of dry, binder-free free-flowing inorganic powder relatively simple. Preferably, the height  $h_w$  of the wedge-shaped structures is in the range  $0.5 \times d_{aw} \leq h_w \leq 50 \times d_{aw}$ , where  $d_{aw}$  is the distance 25 between the first wall 3 of an element 2 and the second wall 4' of an adjacent element 2 at the location of the supporting member 1. According to the invention, the light issuing from the light-collimating system (indicated by the arrow  $L_{out}$  in Figure 1A and 1B) is collimated.

Figure 3 shows schematically a top view of a diaphragm-like adjustable wedge-shaped structure. In this embodiment, the wedge-shaped structure is configured from 30 a plurality of walls 23, 23', ..., 24, 24', ... forming a diaphragm-like wedge-shaped structure with respect to the supporting member 1. The plurality of walls, comprising at least one first wall 23, 23', ... and at least one second wall 24, 24', ... function as (reflective) side flaps of

the diaphragm-like wedge-shaped structure. The plurality of first and second walls 23, 23', ..., 24, 24', ... slide past each other when the wedge angle of the walls is changed.

Figure 4 shows schematically a path of a light ray through a detail of the adjustable wedge collimator (the supporting member is not shown). A first wall 3 and a second wall 4' of an adjacent element are shown. The first wall 3 is provided with a specular reflecting surface 23 and the second wall 4' is provided with a specular reflecting surface 24'. In the example of Figure 4 a light ray is incident on the open wedge (refractive index  $n=1$ ) at an angle  $\theta_i$  (with respect to the normal, parallel to  $L_{in}$  in Figure 1) and is reflected at the specular reflecting surface 23 on the first wall 3 that makes an angle  $\theta_w$  (wedge angle) with the normal. In the example of Figure 4 only one reflection takes place and the light ray issuing from the wedge collimator makes an angle  $\theta_e$  with respect to the normal. The number of reflections depends on the incident angle  $\theta_i$ , the height  $h_w$  of the elements, and the wedge angle  $\theta_w$ . The collimation angle  $\theta_c$  with respect to the normal refers to the largest angle  $\theta_e$  at which a light ray can emerge from the wedge structure when isotropic light with  $0^\circ \leq \theta_i \leq 90^\circ$  with respect to the normal is incident upon the wedge-shaped structure.

In practice, the adjustability of the wedge angle  $\theta_w$  is in the range from approximately  $0^\circ$  to approximately  $25^\circ$ , preferably  $0 \leq \theta_w \leq 15^\circ$ . Figure 4 shows a typical example of a view graph of the collimation angle  $\theta_c$  as a function of the wedge angle  $\theta_w$  for the adjustable wedge collimator. A collimation angle  $\theta_c$  of approximately  $46^\circ$  is reached for a wedge angle  $\theta_w$  of between approximately  $11$  and  $22^\circ$  (see the part of the curve in Figure 4 denoted with (2) in which at maximum two reflections occur in the wedge-shaped structure). Higher values of the wedge angle are unattractive because this would lead to an aperture becoming too low. By lowering the wedge angle  $\theta_w$ , a collimation angle  $\theta_c$  of approximately  $50^\circ$  is reached for a wedge angle  $\theta_w$  of approximately  $8^\circ$  (see the part of the curve in Figure 4 denoted with (3) in which at maximum three reflections occur in the wedge-shaped structure). By further lowering the wedge angle  $\theta_w$ , a collimation angle  $\theta_c$  of approximately  $55^\circ$  is reached for a wedge angle  $\theta_w$  of approximately  $5^\circ$  (see the part of the curve in Figure 4 denoted with (4) in which at maximum four reflections occur in the wedge-shaped structure). By additionally lowering the wedge angle  $\theta_w$ , a collimation angle  $\theta_c$  of approximately  $60^\circ$  is reached for a wedge angle  $\theta_w$  of approximately  $3^\circ$  (see the part of the curve in Figure 4 denoted with (5) in which at maximum five reflections occur in the wedge-shaped structure). By further lowering the wedge angle  $\theta_w$ , eventually, a collimation angle  $\theta_c$  of  $90^\circ$  is reached

for a wedge angle  $\theta_w$  of  $0^\circ$  (see the part of the curve in Figure 4 denoted with (6) in which the number of reflections rapidly increases).

The scope of protection of the invention is not limited to the embodiments given. The invention resides in each novel characteristic and each combination of 5 characteristics. Reference numerals in the claims do not limit the scope of protection thereof. The use of the verb “comprise” and its declensions does not exclude the presence of elements other than those specified in the claims. The use of the indefinite article “a” or “an” preceding an element does not exclude the presence of a plurality of such elements.